

# Astrophysical violations of the Kerr bound as a possible signature of string theory

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In 4D general relativity, the angular momentum of a black hole is limited by the Kerr bound. We suggest that in string theory, this bound can be breached and compact black-hole-like objects can spin faster. Near such “superspinars,” the efficiency of energy transfer from the accreting matter to radiation can reach 100%, compared to the maximum efficiency of 42% of the extremal Kerr (or 6% of the Schwarzschild) black hole. Finding such superspinning objects as active galactic nuclei, GBHCs, or sources of gamma ray bursts, could be viewed as experimental support for string theory.

] String theory is a popular candidate for quantum theory of gravity, but robust experimental tests still seem out of reach. Two areas where string theory could make contact with the real world are usually suggested: high-energy particle physics, and cosmology. However, cosmological questions require the control of time-dependent backgrounds and spacelike singularities, an area where string theory is still rather weak. Similarly, robust predictions for accelerator physics are tied to the problem of the choice of a vacuum solution, also relatively poorly understood despite recent progress.

This paper advocates the point of view that string theory should be applied to areas where it has already demonstrated its strengths. In particular, it has proven exceptionally good at resolving spacetime geometries with various timelike singularities. (The theoretical control over such solutions increases with the increasing degree of spacetime supersymmetry (SUSY).) Such singularities, inconsistent in general relativity (GR), then represent new classes of legitimate compact objects in the string-theory completion of GR. We suggest that such objects may be relevant for the observational astrophysics of compact objects [1, 2, 3]. Relativistic astrophysics is thus another, hitherto underrepresented, area of physics where signatures of string theory should be sought.

Clearly, not all timelike singularities of GR are consistently resolved in string theory. (An example believed to stay pathological in string theory is the negative-mass Schwarzschild metric.) In this paper, we take advantage of the recent progress in understanding objects with angular momentum in string theory. Specifically, we concentrate on the possibility of violating the Kerr bound on the angular momentum carried by compact objects. The existence of such “superspinars” would have significant observational consequences, in particular for AGNs, GBHCs and GRBs. The basic question becomes an experimental one: *Do we observe candidate compact objects that violate the Kerr bound? If so, they can find a natural interpretation in string theory.*

In four spacetime dimensions, spinning black holes with specific angular momentum  $a = J/M$  are described by the famous Kerr solution of GR, given in the Boyer-Lindquist (BL) coordinates (with  $G_N = c = 1$ ) by

$$ds^2 = - \left( 1 - \frac{2Mr}{\Sigma} \right) dt^2 - \frac{4aMr \sin^2 \theta}{\Sigma} dt d\phi + \frac{\Sigma}{\Delta} dr^2 \\ + \Sigma d\theta^2 + \left( r^2 + a^2 + \frac{2Mr a^2 \sin^2 \theta}{\Sigma} \right) \sin^2 \theta d\phi^2 (1)$$

with  $\Sigma = r^2 + a^2 \cos^2 \theta$  and  $\Delta = r^2 - 2Mr + a^2$ . In the case of black holes carrying an electric charge  $Q$ , the relevant solution would be the Kerr-Newman black hole. The absence of naked singularities leads to the Kerr bound,

$$a^2 + Q^2 \leq M^2. \quad (2)$$

In GR, some form of cosmic censorship is usually assumed, and the over-rotating solutions are discarded as unphysical.

The Kerr-Newman family can be embedded, via minimal  $N = 2$  supergravity, into string theory. In the supersymmetric setting, one encounters another important bound: the BPS bound,

$$Q^2 \leq M^2. \quad (3)$$

There is an interesting clash between the two notions of extremality: The SUSY notion implied by (3) and the more restrictive GR one suggested by (2). The status of the BPS bound is much stronger than that of the Kerr bound: It is an *exact* bound, implied in a supersymmetric vacuum by the kinematics of the supersymmetry algebra. On the other hand, the Kerr bound is a consequence of the detailed prejudice about the regions of very strong curvature (for example, if one assumes the exact validity of classical GR); it should thus be viewed as an approximate bound and expected to receive substantial corrections in string theory, possibly enlarging the space of asymptotically observable parameters (such as  $a$ ) that

correspond to legitimate compact objects. In this sense, the cosmic censorship conjecture would be invalid in its most naive GR form: Some “naked singularities” of GR would be legitimate not because they hide behind horizons, but because they are resolved due to high-energy effects of the deeper theory. It is indeed important to apply to astrophysical objects lessons learned in effective field theory: Observations at a given energy scales (or spacetime curvature) should not require detailed knowledge of the physics at a much higher energy scale (or curvature). Imposing standard cosmic censorship of GR on astrophysical objects violates this “decoupling principle,” by extrapolating GR into the high-curvature regime.

As our first example where a breach of the Kerr bound is achieved in string theory in a controlled setting, consider a class of SUSY solutions in  $4+1$  dimensions known as the “BMPV black holes” [4]. They are solutions of minimal supergravity, with self-dual angular momentum  $J$ , mass  $M$  and electric charge  $Q$ . The BPS bound requires  $|Q| = M$ , but puts no restriction on  $J$ . The BMPV solutions satisfying the BPS bound have a horizon area  $A = \sqrt{Q^3 - J^2}$ . The Kerr bound analog thus requires

$$J^2 \leq Q^3. \quad (4)$$

The SUSY BMPV solutions are extremal black holes for  $J \leq Q^{3/2}$ , and naked singularities for  $J > Q^{3/2}$ . In fact, the situation is even worse: The naked singularity is surrounded by a compact region of closed timelike curves, making it a naked time machine. It appears puzzling that string theory contains a perfectly supersymmetric solution with such apparently pathological causal features.

A stringy resolution of this paradox has been presented in [5]. The pathological core of the solution is excised by a spherical domain wall made out of microscopic constituents (*i.e.*, strings and D-branes) that carry the same total charge and mass as the naked BMPV solution. The outside geometry stays intact, but the pathological inside has been replaced by a causal portion of the Gödel universe solution [6]. In this way, the BMPV solution and the Gödel solution solve each other’s causality problems! The dynamics of the domain wall implies that consistent solutions now satisfy

$$J^2 \leq (Q + R)^3, \quad (5)$$

where  $R$  is the radius of the domain wall. In this way, the Kerr bound (4) has been relaxed due to a stringy effect, allowing a larger class of compact objects in string theory compared to classical GR. Note that there is now no bound on  $J$ , but for large enough  $J$  the domain wall becomes so large that the object is not inside its Schwarzschild radius, and is no longer sufficiently “compact”. (Clearly, objects larger than their Schwarzschild radius are not subject to the Kerr bound. The violation of the Kerr bound is of interest only for objects sufficiently compact, and we restrict our attention to those.)

Note also that even for  $J$ ’s that violate the original bound (4), the resolved solution is described at long distances by the BMPV metric, valid all the way to the domain wall. There, supergravity is finally modified, just before one extrapolates the GR solution to the pathological region.

Once the Kerr bound has been breached in the supersymmetric setting and in  $4+1$  spacetime dimensions, one should expect this phenomenon to be generic in string theory; it should extend to  $3+1$  dimensions and to vacua with supersymmetry either spontaneously broken or absent altogether. Various such solutions are indeed known. The solutions of heterotic string theory found in [7] look from large distances  $3+1$  dimensional, and as if sourced by a naked over-rotating singularity. However, their core is resolved by Kaluza-Klein modes of two extra dimensions compactified on a torus: Instead of a naked singularity, the core contains a periodic array of black holes along the compact dimensions. Thus, an object violating the Kerr bound of GR in  $3+1$  dimensions becomes legitimate in string theory. Another example comes from reducing black ring solutions such as [8] with residual angular momentum. These reductions typically have a multi-center structure and extra  $U(1)$  fields which drive angular momentum up via dipole moments. Outside of SUSY, there exist extremal Kaluza-Klein black holes [9, 10] with a slow rotation phase and a fast rotation phase separated by a singular configuration. This list is far from exhaustive, but the known solutions have a common thread: A geometry described by a forbidden GR solution is resolved by high-energy GR modifications at the core, typically via brane expansion and the formation of an extended bound state with dipole moments.

Having established the possibility of breaching the Kerr bound for compact objects in string theory, we now return to our Universe of  $3+1$  spacetime dimensions. Realistic astrophysical black holes are uncharged, and thus described – in the long-distance regime where GR holds – by the Kerr solution (1). At this stage, string theory does not allow enough control over solutions far from SUSY; hence we cannot present a detailed mechanism for resolving the over-rotating Kerr singularity with the level of rigor comparable to the examples above. Given the lessons learned from those examples, however, we will *assume* that the Kerr black hole in string theory behaves similarly, *i.e.*, we assume that a resolution of the Kerr singularity exists for angular momenta violating the Kerr bound and with the metric outside of the central stringy core given by (1) in the over-rotating regime  $a^2 > M^2$ .

In the vicinity of the singularity, we expect large stringy modifications. Just like the over-rotating BMPV solution, the over-rotating Kerr would be a naked time machine, with closed timelike curves in the region  $r < 0$ . If this solution is to be consistent, this pathological region must be excised or otherwise modified by stringy sources. This form of chronology protection might be generic in string theory [6, 11]. Thus, we assume that the region

below some  $r = \epsilon > 0$  has been so modified.

How much do we need to know about the detailed resolution mechanism at the core of the solution? This question is related to the “decoupling principle” mentioned above. Given the current absence of a precise model, we can only study questions that do not depend on the details of the resolution in the high-curvature region at the core. Luckily, some of the most interesting astrophysical effects take place at distances sufficiently far from the core, where GR is valid and the details of the core dynamics are largely irrelevant. This is so because of a fortunate feature of the Kerr metric in  $3+1$  dimensions: As we approach  $a = M$  from below (by dialing the value of  $a$ , not by a physical process), the size of the horizon depends on  $a$  in a manner reminiscent of the order parameter during a first-order phase transition; it approaches a nonzero limiting value  $\sim M$ , instead of shrinking to zero area and infinite curvature. This creates a useful separation of scales for compact objects with spins not too far above the Kerr bound: The astrophysically interesting regime will be at  $r \sim M$ , far from the stringy core for  $M$  of astrophysical interest.

If such “Kerr superspinars” existed as compact objects in our Universe, how would one observe them? Just as we search for black hole candidates, we should search for superspinars in a number of astrophysically relevant situations: long-lived ones as candidates for active galactic nuclei (AGN) [1] or galactic GBHCs [12], and those that develop an instability as possible mechanisms for GRBs [3].

In the case of AGNs, the main reason supporting the black-hole paradigm [1, 2, 13] is their exceptionally high luminosity, which suggests that they are powered by an accretion process of high efficiency. We claim that superspinars would likely be among the most luminous objects of comparable mass. The simplest model of energy production by compact objects assumes a thin accretion disk along the equatorial plane. Accreting matter moves along direct circular stable orbits, losing angular momentum slowly due to viscosity. In the process, its energy is radiated to infinity, until it reaches the innermost stable circular orbit (ISCO). Then it plunges into the black hole and the remainder of the rest mass is lost. The efficiency of the process is thus measured by the rest mass at the ISCO [2, 14]. Any realistic situation is likely much more complex, but for our purposes it will suffice to adopt this simple picture.

For the Schwarzschild black hole, the ISCO is at  $r = 6M$ , reaching closer to the horizon with increasing  $a$  of the Kerr solution, all the way to  $r = M$  at  $a = M$  [2, 14]. (This is a well-known artefact of the breakdown of BL coordinates at  $a = M$ ; the ISCO at extremality is still a nonzero proper distance above the horizon.) The efficiency of accretion rises from  $\sim 6\%$  at  $a = 0$  to  $1 - 1/\sqrt{3} \sim 42\%$  at extremality.

For superspinars, the equatorial orbits are governed by

the effective potential

$$V(r) = \frac{L^2}{2r^2} - \frac{M}{r} + \frac{1-E^2}{2} \left(1 + \frac{a^2}{r^2}\right) - \frac{M}{r^3}(L - aE)^2, \quad (6)$$

with  $L$  the specific angular momentum and  $E$  the energy at infinity per unit mass of the probe. The ISCO is where the two roots of  $V'(r)$  coincide while  $V(r) = 0$ . It is particularly interesting to look for the value of  $a/M$  at which the efficiency of accretion reaches 100%. This happens when the ISCO has  $E = 0$ , at

$$a/M = \sqrt{32/27} \approx 1.0886, \quad (7)$$

*i.e.*, for over-rotation by less than 9%. At that point, the ISCO has been dragged even deeper into the solution, to  $r = 2M/3$ . (Stangely, the same ratio  $32/27$  makes an appearance in  $4+1$  dimensions, as the ratio of the maximum angular momentum of the neutral black hole and the minimal angular momentum of the black ring.) This is the minimal value of  $r$  that the ISCO can reach as  $a$  varies. For a supermassive superspinar, the ISCO is in the region of relatively weak curvature at large proper distance from the (resolved) singularity, hence insensitive to the details of the dynamics of the core in string theory. A particle at the direct ISCO for  $a/M$  given by (7) carries negative specific angular momentum  $L = -2M/\sqrt{27}$  and its accretion will lower the value of  $a$ . Thus, accretion of matter from ISCO will generally push  $a/M$  of superpinars from higher to lower values. In any case, due to the lowering of the ISCO and consequently the very high efficiency of the accretion process, superspinars are likely to be very luminous during their active phase.

The available data strongly suggest that most AGNs will carry significantly high values of  $a/M$ , perhaps requiring on average as much as 15% efficiency [15]. Many objects spin significantly faster [12, 16], near the Kerr bound (or its refinement due to Thorne [17]). Among AGNs, one of the most famous examples is the Seyfert I galaxy MCG-6-30-15 [18]; some GBHCs are also rapidly rotating (see, *e.g.*, [12]), for example XTE J1650-500.

A useful signature of the specific angular momentum of compact objects comes from their X-ray spectroscopy, in particular, the shape of the  $\sim 6.4$  keV fluorescent Fe  $K\alpha$  emission lines associated with the innermost regions of the accretion disk [19, 20]. In a number of notable examples, very broad red wings of these lines have been observed, strongly suggesting high values of  $a$ . While such findings are typically analyzed under the strict assumption that the Kerr bound holds, it would be interesting to see if some of the observations are compatible with the emission from the accretion disk near the ISCO of a slightly over-rotating superspinar. Future missions, in particular *Constellation-X* and *LISA*, will provide crucial data leading to the measurement of angular momenta

of compact objects with larger accuracy, possibly testing whether any of them breach the Kerr bound.

We conclude this paper with miscellaneous comments:

- Kerr superspinars do not have event horizons, but when they spin only slightly above the Kerr bound they exhibit such a deep gravitational well that any escape requires essentially cosmological time scales. A less teleological concept replacing the event horizon may be needed to describe this properly. It turns out that the Kerr superspinar has a surface  $\mathcal{S}$  at  $r \sim M$  such that the expansion of null geodesics orthogonal to  $\mathcal{S}$  and pointing outwards (to larger  $r$ ) at fixed  $t$  is zero. Thus, the time-like surface  $\mathcal{S}$  can play the role of a holographic screen – an important concept in quantum gravity and string theory – even though it does not satisfy the definition [21] of a dynamical horizon.

- Despite the absence of the event horizon, the Kerr superspinar maintains an ergoregion  $\mathcal{E}$ , with boundary at  $r = M \pm \sqrt{M^2 - a^2 \cos^2 \theta}$ . For  $a > M$  this only has solutions for  $\theta$  smaller than some  $\theta_c < \pi$ : The ergoregion now fills a torus, with openings along the axis of rotation. Interestingly, this phenomenon could facilitate the formation of relativistic jets. We envision a “tea-kettle effect”: Particles falling in from ISCO are trapped by the gravitational well, producing high pressure in the central region, with the natural escape route along the rotation axis where particles do not have to overcome the frame dragging of the ergoregion. This could be further enhanced by the spin-orbit interaction between the accreting matter and the superspinar [3], and by electromagnetic effects in magnetized accretion disks, such as those involved in the Blandford-Znajek process.

- A next step beyond the scope of this paper is the study of possible instabilities of superspinars, which can be two-fold: Those of the stringy core, requiring a detailed stringy model; and the universal low-energy instabilities visible in GR approximation, such as the ergoregion instability [22].

- A string-theory model of superpinars might involve a spherical domain wall similar to that of the  $4 + 1$  example above. However, an even simpler option suggests itself: Could F-strings or D-strings serve as candidate superspinars? Recall that string theory contains another fundamental bound: the Regge bound relating the mass and angular momentum of F-strings. Intriguingly, only in  $3 + 1$  dimensions is the Regge bound qualitatively of the same form as the Kerr bound.

- In classical GR, other solutions representing naked singularities with angular momentum are known, such as [23]. We have confined our attention only to Kerr superspinars, but other possibilities should also be studied.

- Another question is that of the possible origin of superspinars. Can one overspin an existing Kerr black hole by an adiabatic physical process? Preliminary analysis suggests that the answer is probably negative, and that superspinars and black holes should be viewed as two dis-

tinct phases of compact objects separated by a barrier at  $a = M$ . This suggests that superspinars could not be created by collapse of ordinary matter in galaxies. If so, superspinars in AGNs could still be primordial remnants of the high-energy phase of early cosmology when stringy effects were important. This should be studied together with the time-scale problem [1] in models of galaxy formation, which suggests the existence of rather massive seed nuclei in galaxies at surprisingly early times.

We hope that the ideas presented in this paper will trigger further investigation in two independent directions: (1) the theoretical search for detailed models of superspinars in string theory or in phenomenological models; (2) an experimental search for observational signatures of superspinars in our Universe. Finding compact objects that rotate faster than the Kerr bound would be a strong signature of strong-gravity modifications of GR. String theory would then represent an arena in which such results could be naturally interpreted.

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